

Anisotropic flow and other collective phenomena measured in Pb-Pb collisions with ALICE at the LHC

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Recent results of the anisotropic flow measurements by the ALICE Collaboration at the LHC are reviewed. Directed, elliptic, triangular, and quadrangular flow are presented differentially vs. transverse momentum, pseudo-rapidity, and the collision centrality for charged and identified particles. Experimental probes of local parity violation using the charge dependent azimuthal correlations with respect to the reaction plane are also discussed.

§1. Introduction

An azimuthal anisotropic flow describes a collectivity among particles produced in heavy-ion collision, and it is recognized as one of the key observable which provides information on the early time evolution of the nuclei interaction. This ISMD2011 Conference proceedings highlight recent results by the ALICE Collaboration from the anisotropic flow measurements for Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ GeV. Current status of probes of parity symmetry violation in strong interaction using the charge dependent azimuthal correlations with respect to the reaction plane is also discussed.

§2. Anisotropic flow, fluctuations, and non-flow correlations

Anisotropic transverse flow is usually quantified by the coefficients (harmonics) in the Fourier decomposition of the azimuthal distribution of particles with respect to the reaction plane. The collision reaction plane, which is defined by the impact parameter and the colliding nuclei direction, is not known experimentally and the anisotropic flow coefficients can be only extracted from azimuthal correlations between produced particles (for review of the anisotropic flow measurement techniques see¹). The main challenge in the anisotropic flow measurement is to disentangle contribution from correlations not related to the reaction plane (so called non-flow correlations), and to understand the impact on the measured flow from the event-by-event fluctuations (e.g. due to fluctuating energy density in the overlap zone of two nuclei).

Figure 1(a) shows a systematic study of non-flow and flow fluctuations for the elliptic flow, v_2 , measured for Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ GeV. The magnitude of non-flow effects is driven by the difference between v_2 estimated from the two-particle azimuthal correlations without ($v_2\{2, |\Delta\eta| > 0\}$) and with ($v_2\{2, |\Delta\eta| > 1\}$) pseudo-rapidity separation between correlated particles which greatly suppress non-flow effects from short-range correlations. Flow fluctuations can be estimated from the difference between the results from two-particle correlations with a large rapidity gap and those from multi- (4, 6, and 8) particle cumulants (for an estimate of the

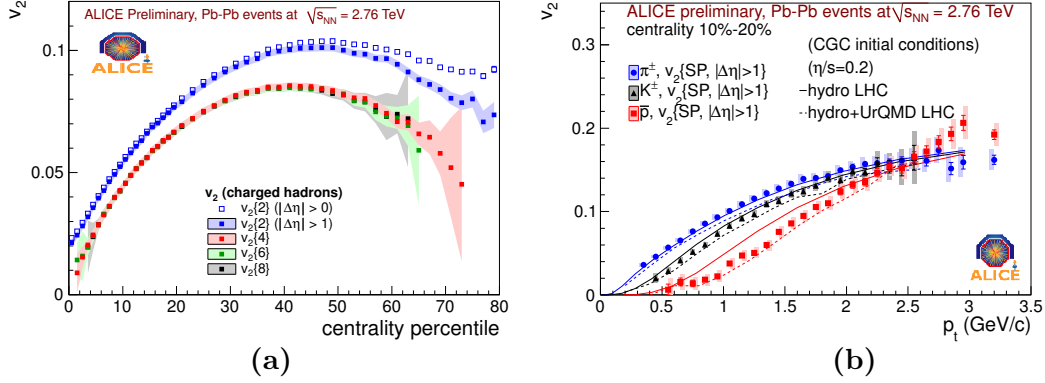


Fig. 1. Elliptic flow, v_2 , measured for Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. (a) v_2 of charged particles vs. centrality, (b) v_2 vs. transverse momentum for pions, kaons, and anti-protons. Figure (a) taken from²⁾ and figure (b) from⁴⁾.

elliptic flow fluctuations under the assumption of the small or Gaussian fluctuations see³⁾). The results in Fig. 1(a) show that both flow fluctuations and non-flow (mainly for the peripheral collisions) are significant and have to be seriously taken into account when comparing measured anisotropic flow with theoretical calculations.

§3. Elliptic flow of identified particles

Since the success of the ideal hydrodynamic description of the elliptic flow, v_2 , for the central Au-Au collisions at RHIC⁵⁾, the hydrodynamics is considered as the most appropriate theory to describe a thermalized phase in the time evolution of the system created in a heavy-ion collision. An important test of the hydrodynamic description at the LHC is the interplay between radial (azimuthally symmetric radial expansion) and anisotropic flow which result in the mass splitting of the elliptic flow at small transverse momenta. Figure 1(b) shows the elliptic flow of pions, kaons, and anti-protons vs. particle transverse momenta, p_t , measured with the scalar product¹⁾ (SP) method. The mass dependence of v_2 at low transverse momenta, $p_t < 2.5$ GeV/c, is well reproduced by viscous hydrodynamic model calculations⁶⁾ with a color glass condensate initial condition (solid lines in Fig. 1(b)). Agreement with data, especially for protons, is improved when adding a hadronic cascade phase into the model calculations (dashed lines in Fig. 1(b)). Figure 2(a) shows elliptic flow of pions, kaons, and anti-protons scaled with the number of constituent quarks, n_q ($n_q = 2$ for mesons, and $n_q = 3$ for baryons), vs. transverse kinetic energy per quark, $(m_t - m_0)/n_q$. The observed approximate scaling of v_2 with the number of quarks in the range of $p_t \sim 2 - 3$ GeV/c ($m_t \sim 0.6 - 1.0$ GeV/c²) reflects collectivity at the quark level and suggest that the system evolved through the phase of deconfined quarks and gluons.

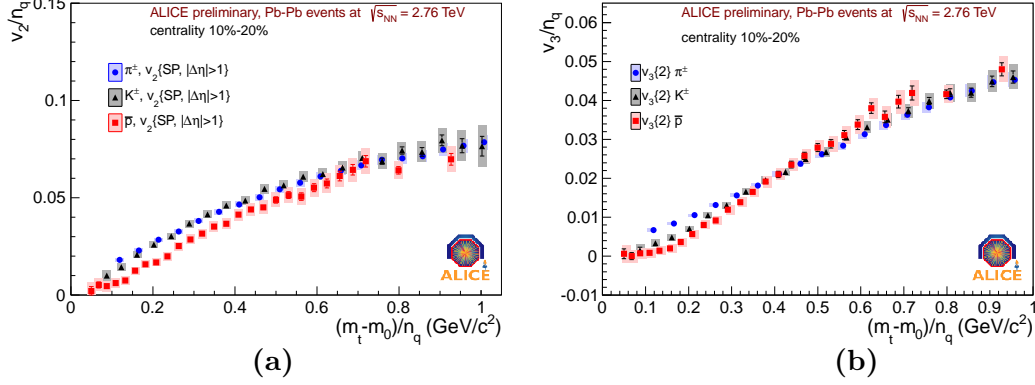


Fig. 2. (a) Elliptic, v_2 , and (b) triangular, v_3 , flow measured with the scalar product (SP) method for Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. Elliptic and triangular flow are scaled with the constituent number of quarks and plotted vs. transverse kinetic energy per quark. Figures taken from⁴⁾.

§4. Triangular and higher harmonic flow

Recent progress in understanding the connection between the anisotropic flow and the fluctuations of the energy density in the initial state of the heavy-ion collision showed that not only the dominant elliptic flow component is important, but that other harmonics such as triangular flow are crucial for the realistic description of the system created during the collision (see⁷⁾ and references therein). Figure 3(a)

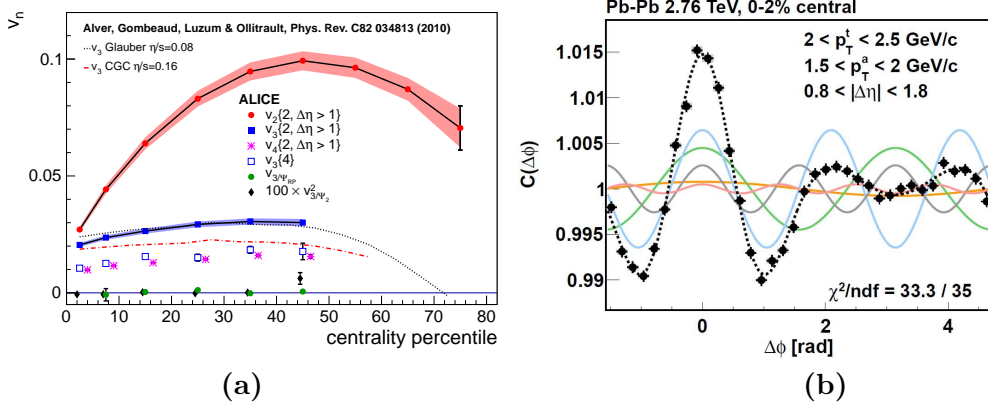


Fig. 3. (a) Elliptic, triangular, and quadrangular flow vs. collision centrality measured for Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. (b) Two-particle azimuthal correlations measured with large ($|\eta| > 1$) rapidity separation between particles and their decomposition into anisotropic flow harmonics. Figure (a) taken from^{3), 7)} and figure (b) from⁸⁾.

shows elliptic, triangular, and quadrangular flow vs. collision centrality measured with two- and four-particle correlations for Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. Measured triangular flow, v_3 , behaves as it is expected for collective correlations from the fluctuations of the initial geometry, i.e. i) weak centrality dependence follows calculations with fluctuating initial condition (solid blue squares vs. dotted black

line), ii) “proper” ratio of $v_3\{2\}/v_3\{4\} \approx 2$ which is expected for the case of pure fluctuations⁹⁾, and iii) no correlation of v_3 with respect to the true reaction plane (v_3 measured with the reaction plane estimated from deflection of neutron spectators is consistent with zero, see green points in Fig. 3(a)), iv) no correlation between v_3 and the azimuthal modulations in the second flow harmonic, v_2 (black diamonds in Fig. 3(a)). Another evidence for the collective origin of the triangular flow is the similar mass splitting and the number of quark scaling to that of elliptic flow which is demonstrated in Fig 2(b). Note that in contrast to the v_2 results in Fig. 2(a), there is no pseudo-rapidity separation between correlated particles in v_3 measurements which may results in the additional bias at small $(m_t - m_0)/n_q$ values.

It is remarkable that including higher-order flow harmonics allows to reproduce the “ridge” and “Mach-cone” features of the two-particle azimuthal correlations at low transverse momenta (see Fig. 3(b)), which were originally interpreted as results of the propagation of the hard probe (e.g. jet) through the dense medium.

§5. Directed flow

Directed flow, v_1 , is sensitive to the earliest, pre-equilibrium, times in the evolution of the system (see¹⁾ and references therein). Figure 4(a) shows v_1 of charged

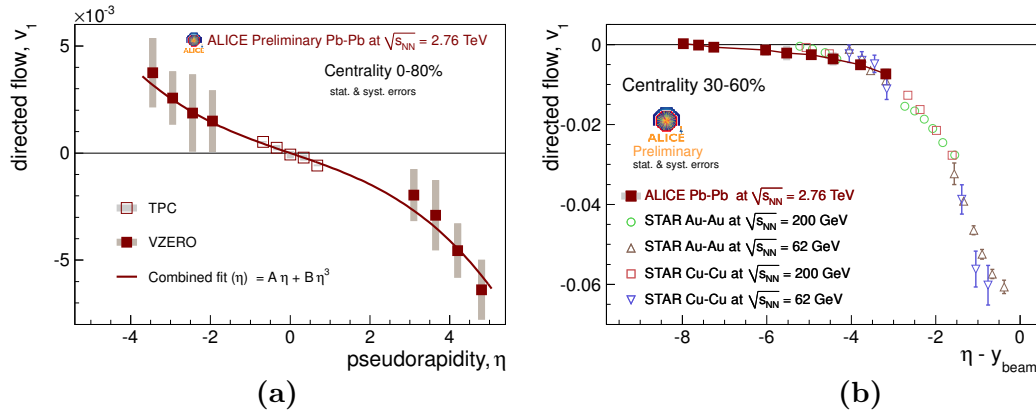


Fig. 4. Directed flow, v_1 , for Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. (a) v_1 over large rapidity range, $|\eta| < 5.1$. (b) longitudinal scaling of v_1 . Figures taken from¹⁰⁾.

particles measured in a wide rapidity range with the reaction plane estimated from the deflection of the spectator neutrons at beam rapidity. The absolute sign of directed flow is fixed in the measurement by the same convention as used at RHIC, i.e. spectators with $\eta > 0$ possess a positive v_1 . The measured negative slope of v_1 as a function of pseudo-rapidity is opposite to the predictions for LHC energies from the quark-gluon string model with parton rearrangement¹¹⁾ and fluid dynamical calculations¹²⁾ which suggest a much stronger signal with a positive slope of v_1 . Figure 4(b) shows v_1 measured as a function of beam rapidity which is consistent with the longitudinal scaling previously observed at RHIC energies.

§6. Probes of local parity violation in strong interaction

The extreme magnetic field created during a non-central relativistic heavy-ion collision may spontaneously excite instantons and sphalerons from the QCD vacuum which violates parity symmetry of the strong interactions. It is predicted by Kharzeev *et al.*¹³⁾ that this may result in the experimentally observable separation of charges along the magnetic field. Since the magnetic field is perpendicular to the collision reaction plane, Voloshin¹⁴⁾ proposed to use the anisotropic flow measurement technique to experimentally probe the effects of charge separation. Figure 5(a) shows

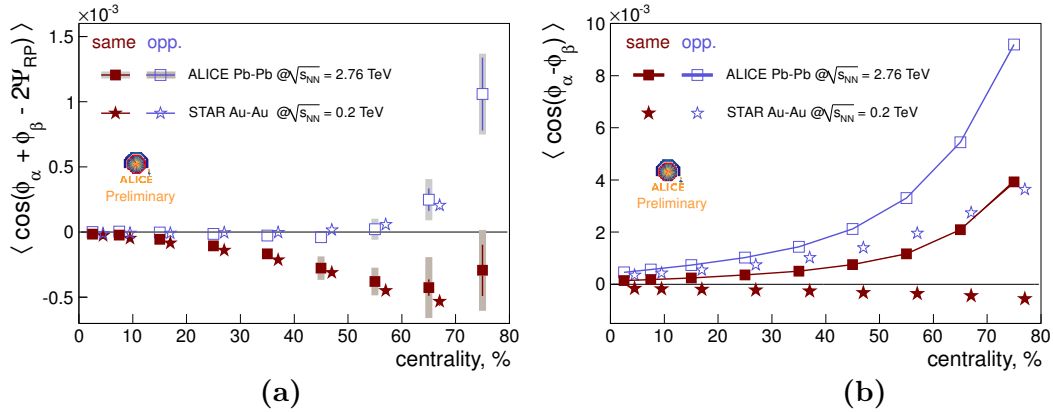


Fig. 5. Charged dependent azimuthal correlations vs. centrality measured for Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV and Au-Au collisions at $\sqrt{s_{NN}} = 0.2$ TeV: (a) two-particle correlations with respect to the reaction plane, (b) 1st harmonic two-particle correlations. Figures adapted from¹⁵⁾.

the experimental results for the charge-dependent two-particle correlation with respect to the reaction plane: $\langle \cos(\phi_\alpha + \phi_\beta - 2\Psi_{RP}) \rangle$, where $\phi_{\alpha,\beta}$ is the azimuthal angle and α, β charge of the particle, and Ψ_{RP} is the reaction plane angle. Clear charge separation is observed at both RHIC and LHC energies with a very similar magnitude and centrality dependence of the correlations. The $\langle \cos(\phi_\alpha + \phi_\beta - 2\Psi_{RP}) \rangle$ observable has direct sensitivity to the event-by-event charge fluctuations, but it is parity even and thus is sensitive to effect unrelated to the symmetry violation. The presence of parity even background correlations which contributes to the measured charge separation at RHIC and LHC significantly complicates the interpretation of the data. Among possibly large contributions from the parity even backgrounds are flow fluctuations in the first flow harmonic¹⁶⁾ and effects of local charge conservation¹⁷⁾. Figure 5(b) presents the 1st harmonic two-particle correlations, $\langle \cos(\phi_\alpha - \phi_\beta) \rangle$, which in contrast to the $\langle \cos(\phi_\alpha + \phi_\beta - 2\Psi_{RP}) \rangle$ show opposite sign at LHC than at RHIC for the same charge correlations. Results for the $\langle \cos(\phi_\alpha - \phi_\beta) \rangle$ correlator are dominated by the parity conserving background sources and this may provide additional insights on the origin of the measured charge separation. Currently, large theoretical uncertainties in the estimate of background correlations as well as lack of quantitative predictions from the models which incorporate parity symmetry violation in QCD make the data interpretation difficult and further theoretical developments in

this direction are extremely important.

§7. Summary and outlook

The anisotropic flow harmonics up to the fifth order have been measured for Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ GeV by the ALICE Collaboration at the LHC. Altogether, directed, elliptic, triangular, and quadrangular flow measurements provide strong constraints on the properties of the system created during the heavy-ion collision such as viscosity, initial conditions, and the equation of state. Charge separation of particles with respect to the collision reaction plane, which was first observed at RHIC energies, is now measured for Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ GeV by the ALICE Collaboration at the LHC. The charge-dependent two-particle azimuthal correlations with respect to the reaction plane are very similar to that at RHIC energies, while the background dominated 1st harmonic two-particle azimuthal correlations show a different sign at LHC than at RHIC for the same charge correlations. This provides strong experimental constraints on the possible mechanism of the measured charge separation.

Acknowledgements

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